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REVIEW ARTICLE

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Historical and current usage of per- and polyfluoroalkyl substances (PFAS): A literature review

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Abstract

Background: Per- and polyfluoroalkyl substances (PFAS) have uniquely useful chemical and physical properties, leading to their extensive industrial, commercial, and consumer applications since at least the 1950s. Some industries have publicly reported at least some degree of information regarding their PFAS use, while other industries have reported little, if any, such information publicly.

Methods: Publicly available sources were extensively researched for information. Literature searches were performed on key words via a variety of search mechanisms, including existing PFAS use and synthesis literature, patent databases, manufacturers' websites, public government databases, and library catalogs. Additional searches were conducted specifically for suspected or known uses.

Results: PFAS have been used in a wide variety of applications, which are summarized into several industries and applications. The expanded literature search yielded additional references as well as greater details, such as concentrations and specific PFAS used, on several previously reported uses.

Conclusions: This knowledge will help inform which industries and occupations may lead to potential exposure to workers and to the environment.

KEYWORDS
applications, historical, manufacturing, per- and polyfluoroalkyl substances, PFAS, usage

1 | INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) are a class of synthetically made chemicals. They generally consist of a carbon backbone with fluorines saturating most carbons and at least one functional group, such as a carboxylic acid, sulfonic acid, amine, or other. The carbon backbone may not be exclusively carbon; for example, the backbone of ether-type PFAS include oxygen atoms. The term PFAS is relatively new, and it has only become part of the modern lexicon within the last decade or so.[1] In older references, the term perfluorinated chemicals (PFC) was used, but that term has generally been phased out, partially because it can be confused with the term perfluorinated carbons and because the polyfluorinated chemicals are also of interest. Today, PFAS is generally used for the same group of chemicals once referred to as PFC. There is no official definition of either PFAS or PFC, however, and various definitions can significantly affect what is and is not considered a PFAS.[2] This article also does not conclude what is and is not a PFAS, and in most cases the point is moot for the references used. Many references simply refer to the use of, for example, "fluorosurfactants" or "fluorochemicals," and for purposes of this article, that is taken to mean a chemical is PFAS.

Carbon tetrafluoride, the simplest perfluorocarbon, was first produced in 1886.[3] Other PFCs have been made since at least the 1930s.[4] PFAS with functional groups have been made since at least the 1940s and since at least the 1950s have been used in various industries and products due to their unique properties.[5] The first

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fluoropolymer patent was filed in 1934. Polytetrafluoroethylene (PTFE) was first synthesized in 1938, and due to its unique properties, was used in the Manhattan Project to separate UF_6 isotopes.[6,7] In 1946, DuPont commercialized PTFE.[7] The Manhattan Project instigated a large amount of research into fluorocarbons as they did not react with fluorine in the diffusion plants separating uranium isotopes and were suitable for the harsh conditions of the processes. This include PFAS other than PTFE and other polymers. Several liquid fluorocarbons were required for the work in the Manhattan Project, and large scale manufacturing of perfluoro solvents, oils, and waxes was investigated.[6]

PFAS' very useful chemical and physical properties are due to their molecular structure. The highly fluorinated portion of the PFAS molecule makes them both lipophobic and hydrophobic, but the functional group, which most have, allows them to interact with polar molecules. Generally, PFAS do not degrade through normal chemical, physical, or biological processes although some PFAS, referred to as precursors, degrade to other PFAS. Their resistance to degradation makes PFAS useful in industry at high temperatures or pressures or in corrosive environments. For these reasons, they are used in a wide variety of consumer, commercial, and industrial applications as this article will describe.

PFAS's resistance to degradation, which makes them useful to industry, conversely has caused concern due to their persistence in the environment. At least some PFAS are also persistent in humans and other animals. Starting in 1999, the Centers for Disease Control and Prevention has sampled the general U.S. population's blood for PFAS through the National Health and Nutrition Examination Survey, and PFAS have been found consistently in the majority of the sampled serum. Certain PFAS such as perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS), and perfluorohexanesulfonic acid (PFHxS) have consistently been found in 99% of the sampled population.[8] Further, PFAS have been associated with numerous detrimental health outcomes such as developmental, immunological, cardiovascular, and hepatic effects.[9]

A specific understanding of how, where, when, and why PFAS have been used is critical to comprehending their potential for human and environmental exposure and any potential risk they may pose. This article presents a compilation of information regarding known PFAS manufacturing and industrial uses based on a literature search of existing, assorted references (e.g., scientific journals, books, patents). U.S. regulatory information, primarily that with respect to food packaging, medical use, and pesticides also provided information on PFAS uses. Scientific literature has provided information on uses.[5,10-13] This article provides information that augments the list of known uses. Where possible, it also offers detailed information on known uses. A note of caution: many of this article's references relate to U.S. patents. A patent's existence associated with a particular use does not necessarily mean that use or production of the patented process occurred. However, when multiple patents exist for a similar use, it is likely that at some point that use occurred.

2 | MATERIALS AND METHODS

Literature searches were performed on key words such as "perfluor" or "fluor" via a variety of search mechanisms, such as EPA's Desktop Library, an internal EPA search engine for various publication types, and Google Scholar and Google Patent. Existing PFAS use references were also consulted. Additional searches were conducted in which suspected or known uses were added to key word searches. In instances where a given manufacturer was identified in conjunction with a specific use, the relevant manufacturer's website was searched to confirm information, including Safety Data Sheets (SDS) when available. Searches were also performed using available public government databases to find specific PFAS that are or have been regulated or listed. Several chemical lists, including the "PFAS Structures in DSSTox," were downloaded from EPA's Chemicals Dashboard. The PFAS Structures in DSSTox list filters compounds based on several substructural filters.[14] This list was imported into SAS version 9.4 (TS1M1) (SAS Institute, Cary, NC) and compared to other lists as noted in later sections of this article. When possible, comparisons were performed on Chemical Abstracts Service Registry Number (CASRN) or the Chemicals Dashboard's DTXSID, but in some cases CASRN or DTXSID were not available for a particular list, so comparisons were done based on all available synonyms.

3 | RESULTS

PFAS have been used in a wide variety of applications, which are summarized into 25 broad industries and applications discussed below in alphabetical order. In several cases overlap occurs between applications. For example, textiles have been coated with PFAS for medical use, and thus that use is mentioned in both the textiles and medical use sections. While a few industries could have been combined with other industries, for example, etching, they were kept separate to better describe and to elaborate on the various industries' PFAS-specific uses. As much as possible, the use is described in the industry where the product is made or used within another product and then a briefer mention in the industry where the finished product is used. Hence, coating wiring with PFAS is described in the electronics section, but the coated wiring product is briefly mentioned in other sections such as the transportation industry.

The expanded literature search yielded additional references as well as greater details on several previously reported uses. Unfortunately, like other chemicals, many PFAS are used in such a way that their use is a trade secret, or there is no requirement that their use be stated in a specific application. As such, patents were particularly helpful in identifying information on uses not previously reported.

The list of uses below is not meant to indicate PFAS concentration information related to applications unless specifically noted. In some applications, the product's PFAS concentration may have been de minimis. Unless stated, the information also does not indicate which specific PFAS was used or whether the use is still occurring. Specific PFAS and PFAS groups that were mentioned in the references and identifiable, especially a CASRN or molecular structure, are listed in Supporting Information Table S1 with their acronyms, CASRN, DTXSID, summary of use, reference, and note of article's relevant section.

3.1 | Adhesives

PFAS are used in solvent- and water-based adhesives to ensure complete contact between joining surfaces and retard foaming. Kissa (2001) states fluorinated surfactants should be evaluated at 0.001%, 0.01%, and 0.1% solids on weight of the formulated adhesive. For example, PFAS surfactants added to rubber allow adhesive-less bonding to steel.[11] PFAS is used with urea-formaldehyde adhesive resins for wood particleboard bonding to improve the cold-water swelling and internal bond strength. These improvements occur by reducing the resin's interfacial tension and improving substrate wetting.[12] An EPA Significant New Use Rule (SNUR) also refers to PFAS use in adhesives and states PFOA is used as a surfactant and coating as part of stickers, labels, and parts to which those stickers and labels are attached.[15] OMNOVA Solutions Inc. states that their fluorosurfactants promote uniform surface coverage and improved appearance features and can be used in adhesives applications.[16] DuPont stated that their Zonyl FSN provides tackifier modification, improved wetting, and compatibility with most aqueous- or solvent-based adhesives.[17] Chemguard states their fluorosurfactants are based on fluorotelomer synthesis of predominantly six carbon perfluoro chains, which improve wetting characteristics and increase pore penetration of adhesives.[18]

3.2 | Building and construction industry

PFAS can be used in different applications within the construction industry, which are noted in Table 1. PFAS reduce cement shrinkage[11] and may be used to stabilize aqueous foam used to allow for flowable concrete mixtures.[19] The concrete's water content may be reduced while still allowing the concrete to be fluid.[20] A patent refers to PFAS as a slurry surfactant for cementing a well.[21] Cement tiles containing PFAS are more weather resistant than tiles made with other dispersants.[11] PFAS improve primers used for coating cement mortar.[11] Cement can be coated with PTFE to protect it.[22,23] AkzoNobel Marine & Protective Coatings is said to have developed a fluoropolymer coating to deter the formation of macro- and microfouling on marine structures and industrial processes.[24]

Starting in 1965, polyvinyl fluoride (PVF) was used in low-maintenance house exterior supplies.[3,25] PTFE also can be woven to make architectural fabrics, such as those used in roofs, and can be used to coat fiberglass for tensile structures or long-life structures.[26] Several other PFAS polymers are also noted coating for building and to make into roof and window fabrics and films.[3,7] Filter bags used in baghouses for air emission control can be made with a PTFE membrane bonded to the filter, and the PTFE membrane acts as a permanent dustcake.[27,28] Filter fabric can also be coated with a bath or spray of liquid PTFE resin to protect the filter in corrosive environments.[28]

TABLE 1 Building and construction industry PFAS uses

Air emission filters
Cement tiles
Concrete mixtures
Greenhouse/conservatory windows
House doors
House shutters
House siding
House windows
Marine structures
Roofing
Roof fabrics (architectural)
Skyscraper metal walls coating
Solar application films

Abbreviation: PFAS, per- and polyfluoroalkyl substances.

3.3 | Ceramics and nanostructures synthesis

Supercritical fluids have been investigated to make ceramic powders. PFAS were used in a supercritical carbon dioxide fluid to synthesize ceramics including titanium dioxide and silver chloride.[29] Supercritical fluids with PFAS have also been investigated to synthesize stabilized metal nanoparticles such as copper, silver, iridium, platinum, and palladium. Similarly, fine nitride and oxide particles can be synthesized via the decomposition of the corresponding fluorinated carbon metal complex in supercritical fluid.[30]

3.4 | Cleaning products

Due to surfactant properties, PFAS have been used to lower surface tension and thus to improve wetting, enhance penetration, and improve rinse-off as well as improve antifogging characteristics in many industrial and household cleaning products.[10,12,18,31–35] Types of items where the cleaning products may contain PFAS are listed in Table 2. PFAS used in a detergent reduces wiping streaks and reflection glittering of cleaned glass and in wiper fluid prevents windshield icing.[11] PFAS can be used in cleaners containing strong acids and bases. A typical alkaline cleaner contains 0.01% anionic fluorinated surfactant. PFAS are used in cleaning formulations that remove calcium sulfate scale from reverse osmosis membranes.[11]

TABLE 2 Types of items when PFAS is used for cleaning

Alkaline cleaners
ATVs
Automobile waxes
Bicycle chains
Blades and bits
Cams and pulleys
Car wash products
Carpet spot cleaners
Concrete
Conveyor belts
Countertops
Denture cleaners
Dishwashing liquids
Floor polish
Floors
Glass
Hard surfaces in general
Hinges
Masonry
Metal surfaces (such as airplanes)
Motorcycle chains
Power tools and equipment
Rollers
Shampoos
Slides
Winches
Wood

Abbreviation: PFAS, per- and polyfluoroalkyl substances.

As mentioned above, some cleaners only contain a small percentage of PFAS. However, other cleaners are mostly PFAS. The SDS for 3M's Novec contact cleaner states it contains two PFAS, which combined are 95%–99% by the cleaner's weight.[36] The SDS for 3M's Novec electronic degreaser states it contains the same two compounds but only 15%–35% by weight.[37] Similarly, the SDS for 3M's Novec flux remover states it contains the same two compounds but at 25%–45% by weight.[38] The SDS for 3M's Novec contact cleaner/lubricant states it contains four PFAS, which are 55%–85% of the mixture's weight.[39] Extractable perfluorocarboxylic acids (PFCAs) have been found in commercial carpet-care liquids and household carpet/fabric-care liquids and foams.[40]

Although not exactly cleaning products, lubricants may also contain PFAS. Dry lubricants may have PTFE in them.[41,42] Non-polymer PFAS have been found in bicycle lubricants.[43]

Numerous patents also mention PFAS. A patent for chemical solvating, degreasing, stripping and cleaning agents refers to six carbon length hydrofluoroethers.[44] Another patent mentions the use of perfluoroalkane and perfluorocycloalkane compounds for removing contaminants from surfaces, such as metal, glass, ceramic, plastic, or fabric.[45] Fluorinated sulfonamide surfactants are mentioned in a cleaning solution patent for electronics manufacturing.[46]

3.5 | Coatings, wax, paint, varnish, and inks

PFAS have been used in various coating products to reduce surface tension for substrate wetting, penetration, leveling, spreading, dispersing agents; improving gloss, uniform surface coverage, and antistatic and antifouling properties; and imparting oil and water repellency on various surfaces.[3,10,11,15–18,25,34,47–56] Surface treatment of metals is further discussed in the metal plating section. Perfluorinated urethanes enhance anticorrosive paints' protective properties.[11] Stony material, marble, tiles, cement, glass fabrics, and metals can be protected from atmospheric agents and pollution with a PTFE or polyvinylidene difluoride (PVDF) coating in an aqueous PFAS dispersion.[3,22,23,25,47] Other polymers have also been noted for their stability, low surface energy and chemical resistance when used as coatings for cookware and metals and as powder coatings.[7,25] A list of the different types of coating products that may use PFAS and materials that they coat listed in Table 3 (Paper coating is covered in Section 3.16).

PFAS can be used on glass, metal, or plastic surfaces as an antimist film to prevent surface fogging in humid environments, such as bathrooms, automobile windshields, and eyeglass lenses. PFAS can also be used as an antimist film on glass and plastic cover sheets used in agriculture. PFAS can be blended into transparent polyvinyl chloride, polyethylene, or ethylene-vinyl acetate film to reduce clouding.[11,17] Perfluoro(polyether silanes) can be prepared by reacting PFAS esters or alcohols with silanes and then applied to siliceous surfaces, such as shower panels or bathroom ceramics to facilitate cleaning.[7] Further, they can be used as a surface treatment to make low refractive index resin for optical applications.[15] A patent for a hydrophobic film coating process, with a particular relevance in the optical technical field, particularly with ophthalmic glasses refers to an antifouling, hydrophobic and/or oleophobic top-coat comprising silane-based compounds bearing fluorinated groups, in particular perfluorocarbon or perfluoropolyether group(s).[57] Other patents refer to fluorine-containing surfactants used as antifogging agents for plastic molding materials, films, automobile headlight film, and greenhouse covering material.[58–60] A patent for forming water repellent coatings on glass, magnesium fluoride coated glass, and indium-tin oxide coated glass include a mixture of PFAS and a silane.[61] AGC notes that their SURFLON fluoro-surfactants have surface modification and water and oil repellence properties, which serve as antifogging agents for agricultural film and glasses.[34] PFAS were found in consumer antifog sprays and wipes.[62]

TABLE 3 Coating products or materials coated with PFAS

Adhesives
Agricultural glass and plastic covers (ex. greenhouses)
Automotive finishes
Caulks
Cellulose
Cements
Ceramics
Chemical processing industry equipment such as ducts, reactors, impellers, tanks, pipes, and fasteners
Clearcoats
Cookware/bakeware (household, industrial, commercial)
Dryer drums (commercial)
Fishing rods and reels
Floor waxes
Glass (automobile windshields, automobile headlights, bathroom mirrors, eyeglasses, etc.)
Guns
Grouts
Inks
Metals
Musical instrument strings
Natural stones
Paint
Piano parts including pins and knuckles
Pigments
Plastics and elastomers
Polishes
Resins
Sealers
Sewing machine presser feet
Ski wax (snow skis, snowboards)
Sports Equipment strings (tennis racquet, etc.)
Stains (floor, wood, etc.)
Varnish
Waxes
Wood

Abbreviation: PFAS, per- and polyfluoroalkyl substances.

Extractable PFCAs have been found in floor waxes and stone/tile/wood sealants.[40] PFAS may be used in tiny amounts for coating applications. PFAS used in the manufacturing of architectural coatings or wood coatings, at a maximum concentration of 0.1% by weight and also in the manufacturing of industrial primer coatings for nonspray applications to metal by coil coating application, at a maximum concentration of 0.01% by weight.[15] PFAS are used in floor polishes and latex paints at concentrations of 50–150 ppm to minimize cratering and peeling.[3]

In dyes and inks, they can be used as pigment grinding aids, to combat pigment flotation problems, improve flow, and eliminate snowflaking.[3,10,47,63] They are said to provides pigment compatibility in inks, improved cylinder life in print equipment and better print definition.[17] Waxes used as additives for printing inks can be modified by the addition of PTFE micropowders, which allows for important and useful changes in printing ink properties and print processing characteristics to be achieved.[25] PFAS are noted for use in water-based inks, ink jet inks, and ink masterbatch.[15] Others report PFAS as both toner or printing ink additive.[64] Fluorinated surfactants in ink jet printer inks improve porous or nonporous media's processing and image quality.[12] A patent for ink jet ink compositions states that a fluoro-surfactant in the concentration of 0.001 to 3 wt% reduces nozzle plate ink puddling while enhancing bleed control and reducing coalescence, and Zonyl FSA, Zonyl FS-62, and Fluorad FC-129 are preferred fluoro-surfactants.[65]

Pigment dispersions containing PFAS are stable at high temperatures and can be used in automotive coatings applied by spraying and baking. PFAS can be used as antistats to prevent the buildup of static electricity and dissipate an electric charge formed on the substrate. Amphoteric surfactants function as antistatic agents for magnetic tapes and phonograph records. Anionic fluorinated surfactants have been used as antistats for rubber compositions. Anionic and nonionic surfactants have been used for PVC. A nonionic fluorinated surfactant can reduce the surface charge of polyester film.[11] A patent states that a fluorine-containing surface treatment can act as resin adhesion inhibitors and as agents for mold release, flux barrier, antiadhesion, antiblocking, rear-surface treatment, anti-tacking, and electric wire stripping agents. The patent's fluorine treatment contains polyfluoroalkyl esters or ethers as a copolymer.[66]

Certain PFAS are stated to be used commonly as levelling and wetting agents in waxes and coatings.[40] Ski waxes have been known to use PFAS, and several PFAS have been found in glider powders and solid blocks.[67–70] AGC mentions ski wax as an application for their SURFLON fluoro-surfactants because of their surface modification properties.[34]

A patent refers to fluoro waxes for sports equipment in general.[71] On stringed sports equipment such as racquets, a fluoropolymer coating facilitates stringing, reduces wear and abrasion during use, and improves performance by allowing the smooth stretching and contraction of the strings under impact. Similarly, the fluoropolymer coating on musical instrument strings and fishing rods and reels makes assembly and use easier and protects from contamination and corrosion. The strings can be coated by soaking, spraying, laminating, or with vapor.[72–78] Sewing machine presser feet can be coated with PTFE to allow the foot to glide over fabric that may not move evenly.[79] Similarly, guns can lubricated by fluoropolymers.[80] The U.S. military specified a lubricant for use with ammunition of a 20% fluorocarbon telomer dispersion in 1,1,2-trichloro-1,2,2-trifluoroethane. The specification is now canceled.[81]

Industrial parts can be coated with fluoropolymers to create lubricity. The fluoropolymer is said to enhance corrosion resistance and high temperature resistance.[82]

3.6 | Cosmetics and personal care

PFAS are used in cosmetics as emulsifiers, lubricants, or oleophobic agents. PFAS are also used in hair-conditioning formulations and hair creams to improve lubricity, facilitate wet combing, and render hair oleophobic. Only a small amount (<0.05%) of a fluorinated surfactant is needed to enhance the effectiveness of cationic hair conditioners.[11] PFAS have been used widely in personal care products, such as sunscreen and cosmetics, for oil and water resistance.[83] A patent refers to use of PFAS polymers to microencapsulate a new type of sunscreen.[84] Several patents mention PFAS for use in hand sanitizers.[85-87] Table 4 provides a list of the different cosmetics and personal care products in which PFAS may be found.

The Danish Environmental Protection Agency performed a risk assessment of fluorinated substances in cosmetic products. They scanned label databases for fluoroalkyl substances and other fluorinated compounds. PTFE was noted as an ingredient in several products, and fluorophosphate was listed in four products types. The products are listed in Table 4. They also chemically analyzed different products whose labels identified PFAS as an ingredient. The highest individual PFAS concentration in a product was 3340 ng/g perfluorohexanoic acid. The highest total PFAS concentration in a product was 10,700 ng/g.[88] Similarly, detectable levels of PFAS have been found in cosmetics and sunscreens.[83,89] Clariant's Ceridust 3920 F is a polyethylene wax with PTFE used in cosmetic waxes for creams, sticks, powders, and nail enamel.[90]

A 1958 patent refers to the use of aliphatic PFCAs for use in dental preparations, including toothpastes, dental creams, tooth powders, lozenges, tablets, chewing gums, and dental flosses. The patent states that the compounds exhibit beneficial properties, including antibacteria power as well as absorption and release from proteinaceous material.[91] Another patent states that a perfluoroalkyl surfactant, Zonyl FSA, is an effective antiplaque additive when employed in oral compositions, either alone or in combination with water soluble fluorides. Thus it claims the use of oral compositions with perfluoroalkyl surfactants effectively reduce plaque and gingivitis.[92] Other patents refer to the use of PFAS for their surfactant characteristics to help with fluoride-enamel interaction.[93,94]

Fluoropolymers can be made into dental floss.[95-97] Extractable PFCAs have been found in dental floss and plaque removers.[40]

TABLE 4 Cosmetics and personal care products

Acne treatment
Blush
Blush/highlighter
Brow products
Creams
Dental floss
Dental plaque removers
Eye cream
Eyeshadow
Foundation
Hair conditioner
Hair creams
Hair shampoo
Hand sanitizer
Lip balm/sticks
Lotions
Mascara/lash products
Nail polish
Shaving cream
Sunscreen
Wax

3.7 | Dry cleaning

PFAS are reported to be used in dry-cleaning systems that are replacements for tetrachloroethene-based systems. Several patents describe the use of hydrofluoroethers with other PFAS as an alternative to tetrachloroethene or other solvents. Hydrofluoroethers are said to be less aggressive toward fabrics and to dry faster.[98-100] Similarly, another patent describes the use of dry cleaning with densified carbon dioxide and a surfactant. Fluoroalkyl substances are mentioned as a potential surfactant. The Zonyl series by DuPont is mentioned as a source of fluorinated compounds.[101] Continued patents further describe this system and the use of fluorinated surfactants.[102,103] Another carbon dioxide formulation is described with polysiloxane surfactants, which have a haloalkyl functional group, with fluoroalkyl being preferred.[104] A state of California report on dry cleaning discusses a replacement for tetrachloroethene called PureDry. The mixture contains HFE-7200, FC-43, PF-5070, and PF-5060.[105]

3.8 | Electronics industry

PFAS are used to manufacture numerous electronics listed in Table 5.[3,10] Cured epoxy resins are removed from integrated circuit modules by solutions containing small amounts of PFAS.[11] PFAS are used in low-foaming noncorrosive wetting agents in solders for electrical parts and cleaning of electronic components.[11] Also, PFAS stabilize foam in polar solvents used for pre-welding surface

TABLE 5 Electronics

Aerospace applications
Automotive
Cables and wires associated with communication facilities
Cell phones
Circuit boards
Coaxial cable insulation
Computer cables and networks
Digital cameras
Disk drives
Electrical wiring insulation
Floppy disks
Lithium batteries
Low-frequency plenum cables,
Magnetic recording devices
Magnetic tape
Optical fibers
Printed circuit boards
Printers
Radar systems
Satellite communication systems
Scanners
Solar collectors coating
Zinc batteries

preparation.[12] Fluoropolymers are used as a coating on electronics.[15,47] Numerous manufacturers refer to PFAS use on the inside and outside of electronic devices for water and oil repellence, to protect from moisture and corrosion, to provide easy-to-clean surfaces, reduces dragout in electronics, and improve appearance.[16,18,55,106]

Because of their dielectric, low flammability, chemical and heat resistance, and other mechanical properties, fluoropolymers are widely used in electronics.[7,47] PFOA is noted to be used to make fluoropolymers used in cable and wire insulation for computer networks.[107] Insulated wire may be prepared by coating the wire electrophoretically and treating it with PFAS before baking.[11] Printed circuit boards are laminates of copper on a fiber-reinforced fluoropolymer layer.[3] Electric circuits may be sealed with a material that contains PFAS, and PFAS are also used as lubricants coated on the surface of magnetic recording devices.[11]

PVDF is used in the battery industry as binders for cathodes and anodes in lithium-ion batteries, as battery separators in lithium-ion polymer batteries.[25] A patent for lithium batteries, which includes PVDF as a possible binder on the positive and negative electrode current collector, states that using an electrolyte solution with a specific perfluoro group-containing compound allows for safety and high battery characteristics. The additive has fluorine-substituted ethers, amides, esters, carbonates, phosphate esters, and phosphates.[108] Another lithium battery patent describes using a perfluoro nitrile compound as an electrolyte additive.[109] Research articles note the use of PFAS as lithium battery additives that can limit electrolyte loss and stabilize the solid-electrolyte interphase.[110-112] The lithium-ion battery electrode binders are generally fluorinated polymers.[112] A patent describes fluorinated graphite as a positive-electrode active material in a nonaqueous electrolyte battery.[113]

A 1958 patent discusses the use of PFSA surfactants as an additive to the electrolyte of storage batteries or batteries, such as lead storage batteries and Edison storage batteries. The PFSA lowers the surface tension and allows for rapid and complete wetting-out and penetration by the electrodes' electrolytes. Depending on the specific PFSA used, the electrolyte's PFSA concentration is recommended between 0.005 and 8 g/L.[114] It was previously reported that PFAS continued to be studied as electrolytes.[115] Zinc battery electrolyte may contain PFAS. Mercury used to be used in zinc batteries to decrease the rate of hydrogen evolution, but fluorinated surfactants can be substituted for mercury. Alkaline manganese batteries may have MnO_2 cathodes treated with PFAS.[11] DuPont stated that their Zonyl FSN is a zinc battery scale inhibitor.[17]

PFAS have been used to make polymer electrolyte membrane for fuel cells since 1966. They have been commercially produced since 1972.[116,117] Chemours' perfluorinated membranes used in fuel cells are known by the brand name Nafion and have been the prototypical material for the prevailing class of poly(perfluorosulfonic acid) ionomer membranes. The Nafion PFSA ionomer consists of a tetrafluoroethylene backbone with randomly attached pendant side chains of perfluorinated vinyl ethers. Others have made similar PFSA material for similar use including the Dow experimental membrane (Dow Chemicals), Flemion (Asahi Glass), Aciplex (Asahi Kasei), as well as Hyflon Ion and (SolviCore). Further, increased thermal, mechanical, and electrochemical stability can be achieved by impregnating Nafion into inorganic matrices of clays, silica, phosphotungstic acid, or porous Teflon.[118] Solvay also has a PFSA ionomer membrane sold under the brand name Aquivion, which is used for electrical storage and conversion devices, such as fuel cells, electrolyzers and flow batteries.[119]

PFAS have long been used in heat-exchanging for electric equipment and inert liquids in electronic testing.[3] A 1951 patent states that fluorinated organic compound vapors have outstanding electrical insulating properties and are superior to other gases when evaluated in terms of characteristics, such as breakdown strength, dielectric strength, power factor, and corona formation resistance under similar temperature and pressure conditions. The patent also mentions the use of fluorinated resins for high temperature service insulation.[120] A 1955 patent refers to liquid PFAS as having outstanding properties as vaporizable liquid coolant in an electrical apparatus.[121] Similarly, a 1952 patent refers to perfluorinated organic compounds containing nitrogen, sulfur, or oxygen as dielectric fluids for capacitors.[122] A patent for a type of resistor uses a mixture of

PFAS as the dielectric fluid.[123] U.S. Department of Energy reported on the breakdown strengths of gaseous and liquid insulators in high voltage equipment and noted the important of perfluorination of hydrocarbons to increase dielectric strength.[124]

Perfluorinated ethers can be used as dielectric and heat-exchanging fluids such as for high power transformers and capacitors.[3,125] An IEEE Spectrum article states Fujitsu was releasing a new liquid immersion cooling system for server at data centers that improves the cooling process and eliminates the need for server fans. The cooling bath's coolant is an electrically insulating fluorocarbon fluid manufactured by 3M called Fluorinert.[126] 3M's Fluorinert™ electric liquid series is described as being made of perfluorocarbons and being useful for numerous types of electronic and high-tech equipment.[127] The 3M website for its Novec Insulating Gases states the gases have excellent dielectric performance and can be utilized in gas-insulated switchgear, circuit breakers, gas-insulated lines, and more.[128] The SDS' for the 4710 insulating gas and 5110 insulating gas provide specific PFAS components.[129,130]

3.9 | Etching

PFAS are used as wetting agents in etch baths, including those for glass, plastics, fused silica, and aluminum etchings.[11] They are also used in the semiconductor industry etching as noted below in the semiconductor section. DuPont stated that their Zonyl FSN improves etching efficiency.[17] An EPA SNUR exempt specific PFAS used as a component of an etchant, including a surfactant or fume suppressant, used in the plating process to produce electronic devices.[131]

A patent describes the use of fluorocarbon surfactants in a sulfuric acid-chromic acid bath for a pre-etch stage to condition plastic parts before plating. The patent states that the bath should contain about 4–12 ounces of fluorocarbon surfactant per 100 gallons of bath.[132] Another patent describes etching steel before plating. The etching is performed in a bath with a strong mineral acid and perfluorocarbon sulfonic acids.[133] PFSAs have been used as an aluminum etchant[134] in solutions for glass etching, for planar etching of fused silica, and as wetting agents in plastic etching.[11] Another patent describes the use of etching glass to reduce display surfaces' specular reflection in many hand-held and touch-sensitive electronic devices. A fluorine-based smudge-resistant layer is added to the glass by a reaction with the glass and a fluorosilane, which contains PFAS moieties.[135]

3.10 | Explosives, propellants, and ammunition

Fluorocarbon's first documented use as a pyrotechnic oxidizer was in 1956 in a patent subsequently published in 1964. The pyrotechnic material included a fluoropolymer and a metal, such as magnesium or aluminum for a visual flare composition.[136] In 1956, metal and fluorocarbon material was also first reported in infrared tracking flares.[137] A similar composition flare was reported in a 1958 patent application that was not published until 1997.[138] More research and documentation on these types of compositions was classified for decades.[137]

A magnesium, Teflon (PTFE), and Viton (a vinylidene fluoride and hexafluoropropylene copolymer) composition, commonly known as MTV, provides favorable properties for energetic material use. Other metals besides magnesium have also been investigated for pyrolants. With PTFE pyrolants, PTFE undergoes decomposition and then depolymerizes to yield gaseous tetrafluoroethylene, which, in turn, decomposes further to CF_2 and COF_2. The different metal and fluorocarbon mixtures yield varying products after combustion.[137] Fluorinated polymers were originally found to be conducive as binders but their utility as oxidizers was quickly appreciated. Fluorinated oxidizers have more favorable properties than metal oxidizers due to high heats of formation of metal fluorides compared to that of metal oxides and the relatively high vapor pressure of metal fluorides and oxyfluorides, which volatilize more readily than refractory oxides for most of the energetically favorable metals. Fluorinated oxidizers for metal combustion allow for the generation of more gaseous products than other oxidizers. PTFE has found the broadest range of applications, but straight-chain PFCAs have also been used in energetics.[139]

MTV is used in infrared flares. Metal-fluorocarbon pyrolants may be used in obscurant formulations as their reaction products can yield the desired aerosol species and their reactive processes generate product-aerosolizing energy.[137,139] MTV may be used as igniter pyrolant. Metal-fluorocarbon-based energetics can be used in numerous applications.[137] PFAS have been used to coat reactive metallic powders to protect pyrophoric compositions, to modify their combustion behavior, and to enhance reactivity and hydrophobic properties and have been used as coatings over aluminum powders in core-shell structures.[139-141] In addition, PFAS are used to coat aluminum to prevent its oxidation.[140,142] Aluminum coated with PFAS are also cited for use as propellants in solid rocket propellants and ramjet fuel for civilian and military purposes.[143-145]

An U.S. military specification for ignition pellets consisting of magnesium dispersed in a mixture of solid fluorocarbon polymers states the PTFE plastic molding material will be between 29.5% and 32% by weight and vinylidene fluoride and hexafluoropropylene copolymer will be between 15% and 16.5% by weight.[146] An U.S. military specification for a delay composition of tungsten and fluorocarbon copolymer calls for the copolymer to be one percent of the composition.[147] Examples of uses are in Table 6.

Warheads that require improved mechanical properties and stability at high temperatures will have the wax replaced with thermoplastics, which can include a fluorinated polymer. An example is HMX and 1,3,5-triamino-2,4,6-trinitrobenzene (TATB) mixed with 10 wt% fluorinated polymer.[148] Viton-A and PCTFE are commonly used as binders for plastic bonded explosives (PBX).[149,150] Viton-A based PBX compositions are preferred as they provide better mechanical properties compared to other traditional explosive compositions and thermal stability.[149,151] Numerous fluoropolymer

TABLE 6 Explosives, propellants, and ammunition uses

Agent defeat warheads, which are designed to neutralize biological and chemical warfare agents
Aircraft countermeasures flares
Bullet and shell tracers
Document destruction
Gas generators igniter pyrolant
Ignition pellets
Incendiaries
Mine disposal torches
Propellant charges igniter pyrolant
Propellants
Rocket motors igniter pyrolant
Shot for shotguns
Smoke grenades
Target augmentation flares
Tracking flares
Underwater cutting torches
Underwater explosives
Underwater flares

binders have been investigated for use with TATB.[152] Similarly, fluoropolymers are used with RDX.[153]

The energetic material itself can also be fluorinated.[154] A difluoroamine group provides explosive character, increases density and volatility, lowers the melting point and detonation velocity, and increases impact sensitivity.[148] Different types of PFAS were investigated for use in tagging blasting caps so that they could later be detected at security checkpoints.[155]

Other munitions have used fluoropolymers. Specifically in 2009, U.S. Fish & Wildlife Service approved a tungsten-iron-fluoropolymer shot alloys as a nontoxic substitute for lead for hunting waterfowl and coots. The fluoropolymer is 3.5%–8% by weight.[156] Later in 2012, U.S. Fish & Wildlife Service approved a fluoropolymer coating for steel shot as nontoxic for hunting waterfowl.[157] There are patents for the use of tungsten with fluoropolymer binders to replace lead in ammunition in general.[158,159] In one patent, PFAS are used as solvents and surfactants in making the high density material.[158]

3.11 | Fire-fighting foam

A broad range of groups, including the military (army, air force, and navy), civilian airports, municipal fire departments, and merchant ship crews can be users of aqueous film-forming foams (AFFF), which they use to extinguish hydrocarbon fires at airports, train yards, ships, oil refineries, oil platforms, and other locations.[10,31,47,160] U.S. Naval Research Laboratory tested PFAS in foam beginning in the early 1960s.[161] Perfluorinated carboxylic acids manufactured by electrochemical fluorination were used as components in AFFF from about 1965 to 1975. Perfluorooctanesulfonyl fluoride (POSF)-based AFFF became the product of choice from the 1970s until 2002. Fluorotelomer-based AFFF was produced from 1975 to 2004 but had less market share than POSF-based AFFF.[5] In 2017, the Department of Defense (DOD) edited their military specification for AFFF to include no more than 800 ppb, the quantitation limit by DOD Quality Systems Manual (QSM) 5.1, of PFOA and PFOS in the concentrate.[162]

A 1971 patent for a film-forming fire extinguisher states that film coverage requires 20% by weight fluorine. The fluorinated aliphatic compounds comprising the mixture are described as nonaromatic and can be straight, branched, or cyclic with attached functional groups of carboxylic acid, sulfonic acid, phosphates, or the salts of the previous.[163] A 1974 patent for film-forming fire extinguisher provides examples of mixtures to make one gallon of 6% concentrate. In one example it calls for 55 g and in another example 68 g of the fluorinated surfactant.[164] Commercially available AFFF is generally sold in 1%, 3%, or 6% concentrates to be mixed with the remaining percentage of water.[165,166]

Numerous PFAS are associated with AFFF.[167-169] Protein-based fire-fighting foam uses longer chain PFAS with numerous amide groups linked to the molecule's functional end.[12] Handheld foam fire extinguishers also use PFAS.[35] The PFAS described in an EPA proposed SNUR are described as being used in firefighting foam.[32] Another EPA SNUR specifies PFAS used in fire extinguishing agent components.[15]

PFAS are also used in dry fire-extinguishing agents to make powder non-wettable by hydrocarbons.[11] The chemical formula for 3M's Novec 1230 fire protection fluid describes a PFAS.[170] AGC notes that their SURFLON fluorosurfactants can be used in AFFF.[34] Similarly, Chemguard states their fluorosurfactants can be used in AFFF, AR-AFFF, and protein foams.[13]

3.12 | Medical uses

Potentially, the first considered PFAS medical use was with Clark and Gollan's 1966 experiment involving animals breathing a PFC emulsion.[171] Such emulsions have been examined as substitute blood due to their oxygen-carrying ability.[172,173] That ability is also the reason they have been studied as a possible decompression illness treatment.[3,174] In a recent study, an oxygenated PFC emulsion was used as an intestinal liquid ventilation system administered to mice via rectum and to pigs via surgically inserted tubes in the descending colon to provide vital rescue of experimental models of respiratory failure.[175]

Several patents also discuss perfluorochemical emulsions for drug delivery or substitute blood. One patent relates to an invention for a homogenous water-in-perfluorochemical stable liquid dispersion for acceptable therapeutic drug administration to an animal lung.

The perfluorochemical constitutes greater than 50% by volume of the dispersion, and numerous PFAS are listed as potential mixture parts.[176] Another patent for perfluoroorganic compound emulsions with gas-transporting properties, is intended, in particular, for intravenous administration when compensating for blood losses and for treating various diseases accompanied by hypoxic or ischemic lesions. The emulsion is also intended as contrast and perfusion media. The preferable emulsion mixture contains rapidly eliminable PFAS in an amount of 6 vol. % with slowly eliminable PFAS in an amount of 2.3 vol. %.[177] Another patent refers to the use of PFC emulsion for nitric oxide delivery to treat various conditions. The patent describes the emulsion delivery via numerous different administration routes.[178]

The patents' developmental statuses are unclear, but Fluosol, 20% intravascular perfluorochemical emulsion, is a drug first administered to humans in 1978. After administration, the perfluorochemicals are said to be expired through the lungs. Fluosol was said to be useful for numerous treatments, including oxygen delivery during coronary angioplasty.[3,179] Clinical trials were reported in 1982.[180] Production of Fluosol ceased and its approval withdrawn due to side effects in 1994. Perftoran is another substitute blood medicine or oxygen therapeutic that has been used in Russia, Ukraine, Kazakhstan, and Mexico, and it has been rebranded as Vidaphor in the U.S. and is awaiting clinical trials. Oxygent and several other PFC-based injectable oxygen carriers have been studied in clinical trials.[172,173] PFAS have been used extensively to increase tumor oxygenation and thus improve therapeutic outcomes of therapies, some more than others, such as radiation, photodynamic, chemotherapy, sonodynamic, etc.[3,173]

PFAS can be used in medical diagnostics, including imaging as MRI, ultrasound, positron emission tomography (PET), and multimodal contrast agents.[173] When added to a saline solution, PFAS facilitate dispersion of cell aggregates from tissues and is used to diagnose cell abnormalities.[11] Fluorine-18 (^{18}F) has been a radionuclide of choice for molecular PET imaging. Hence that radionuclide may be incorporated into PFAS for imaging applications. A few PFAS are identified as radiotracers or radiopharmaceuticals labeled with ^{18}F.[181] Perfluorocarbons are said to be useful for creating nanoparticles magnetic resonance molecular imaging and spectroscopy as well as for drug delivery in cancer and cardiovascular disease.[182] A patent refers to the intravenous administration of drug-delivering microspheres. Certain PFAS are among those mentioned as potential compounds to comprise the sphere and the gas inside the sphere.[183] Another patent describes the use of PFAS metal complexes for NMR and x-ray diagnosis, radiodiagnosis and radiotherapy, as well as in MRT lymphography.[184] Similarly, another patent refers to the use of 15-crown-5 ether emulsion form for nuclear magnetic resonance diagnostic spectroscopy for tumor diagnosis and for highlighting specific biological dysfunctions.[185] Medical literature also discusses the use of PFAS as NMR reporter molecules.[181] A similar patent describes methods and apparatus for preparing temperature activated PFAS gaseous precursor-filled liposomes suitable for use as contrast agents for ultrasonic imaging or as drug delivery agents.[186]

Gas or liquid PFAS have been described for use in temporary internal tamponade to treat rhegmatogenous retinal detachment when mixed with heavy silicone oils. PFAS are noted as increasing the successful reattachment.[181,187] PFAS are also referenced in a patent for novel pharmaceutical compositions that may increase neurite (axon and dendrite) outgrowth in nerve cells on inhibitory substrates, and pharmaceutical compositions may be useful in an in vivo treatment of injured, damaged, or diseased nerves in the CNS and PNS when administered to mammals.[188] Some PFAS were reported to be used as foam dampening agents in the pharmaceutical industry.[189]

Fluorine has been added to numerous pharmaceuticals based on natural products or original synthetic pharmaceuticals. Generally, however, only one fluorine atom or a trifluoromethyl group is added to the pharmaceutical.[181] The data files from Food and Drug Administration's Approved Drug Products with Therapeutic Equivalence Evaluations (commonly known as the Orange Book) was downloaded from their website.[190] The drugs listed in it were compared to the compounds in "PFAS | EPA: PFAS structures in DSSTox" in EPA's Chemicals Dashboard[14] after curation by EPA's Chemical Dashboard team, who provided identifiers (The Orange Book data that were downloaded are currently being curated by EPA's Chemicals Dashboard team to be made available publicly as a list in the Dashboard). There were seven compounds in common, and they are listed in Table S1 with their use.[191]

PFAS can be used in the manufacturing of medical devices, including implantable material, devices, parts, and components.[7,95,96,181,192,193] The uses mentioned are listed in Table 7. Plastics for implantable electrochemical sensing devices can be made stretchable using PFAS.[194] PTFE is often used to coat medical devices and surgical equipment.[195,196] PFAS can be used as a coating for medical consumables and bio-consumables.[15] One patent states the polymer chain's fluorinated monomer units aid in increasing the thermal stability, hydrophobicity and oleophobicity of the substrates to which the polymer is applied. The ratio of fluorinated anionic surfactants to other monomers present will usually be 0.5–6 or more (by weight).[193] Volatile PFAS can be used as propellants in inhalers.[197]

PFAS can be used with other compounds to make contact lenses. The use of fluorine-containing groups in contact lens polymers can significantly increase the lens' oxygen permeability and improve deposit resistance.[198-202] Most video endoscopes contain a small amount of PFAS.[10] PFAS are used as a dispersant in radio-opaque ETFE production for accuracy and precision in medical devices, such as angiography radio-opaque catheters and in-dwelling needle catheters.[10] Medical fabrics, including woven and non-woven surgical drapes and gowns, can be treated with side-chain fluorinated polymers to provide water and oil resistance.[47] Extractable PFCAs have been found in non-woven medical garments.[40]

TABLE 7 Medical components and parts

Bags
Blood contact surfaces
Blood substitutes
Breast prostheses and any other device which can act to replace soft tissue
Cannulae
Catheters
Contact lenses
Containers
Device surface coatings
Drainage tubes
Endoprostheses
Fabric liners
Fistulas
Gaskets
Grafts
Guidewires
Hernia patches
Hypotubes
Inhaler propellant
Joint replacement or repair
Joint spacers
Lenses
Mandrels
Needles
Needles cannulas
Oral capsules
Oral tablets
Pericardial patches
Ports
Seals
Shunts
Space-filling or augmentation devices
Stent-grafts
Stents
Stylets
Suppositories
Surgical sheets
Sutures
Synthetic lattices for use in forming a scaffold
Synthetic spinal disks
Transdermal patches
Tubes
Vascular grafts
Vascular protheses
Work surface or clean room surface coatings
Wound care

3.13 | Metal plating and finishing

PFAS have been used as a surfactant, wetting agent, and mist-suppressing agent for chrome plating. They were previously used for decorative chrome plating, but new technology using chromium-III instead of chromium-VI makes that use obsolete. However, PFAS may still be used in hard chrome plating.[10] PFAS use for second-generation wetting agent fume suppresant (WA/FS) was first reported in the chromium plating industry in 1954. The original second generation WA/FS was a PFAS with an amino group. Later PFAS used a sulfonate group. Introduced in the late 1980s and early 1990s, the third-generation WA/FS also contain PFAS with a sulfonate group.[131,134,203] The PFOS derivative that is said to be most frequently used in hard chrome plating is the quaternary ammonium salt tetraethylammonium perfluorooctane sulfonate, which is sold under trade names, such as Fluorotenside-248 and SurTec 960, typically in a 5%–10% solution.[10] A report on WA/FS to suppress emission tested Fumetrol 140 (ATOTECH USA), which had organic fluorosurfactants, including PFOS as the primary active components at 1%–7% of the product. Fumetrol 140 is supposed to be added to the electroplating bath at about 0.25% by volume.[204] The main mist suppressants on the Chinese market are said to be PFOS-based as well as newer PFAS.[205]

Details on their industrial use are described in a US EPA SNUR for PFAS exceptions to the rule as a "fume/mist suppressant in metal finishing and plating baths. Examples of such metal finishing and plating baths include: hard chrome plating; decorative chromium plating; chromic acid anodizing; nickel, cadmium, or lead plating; metal plating on plastics; and alkaline zinc plating."[131] On September 19, 2012, EPA finalized a rule to phase out PFOS-containing WA/FS from hard and decorative chromium electroplating and chromium anodizing tanks. Hard chromium electroplating is described as facilities that plate base metals with a relatively thick layer of chromium using an electrolytic process to provide a finish that is resistant to wear,

TABLE 8 Metal plating products

Aircraft parts (such as wings and landing gears)
Architectural structures subject to high stress and corrosive conditions
Automotive trim
Bicycles
Engine components
Hand tools
Hydraulic cylinders and rods
Large cylinders and industrial rolls used in construction equipment and printing presses
Marine hardware
Metal furniture
Plastic molds
Plumbing fixtures
Zinc die castings

abrasion, heat, and corrosion. Decorative chromium electroplating is described as facilities that plate base materials such as brass, steel, aluminum, or plastic with layers of copper and nickel, followed by a relatively thin layer of chromium to provide a bright, tarnish- and wear-resistant surface. Chromium anodizing facilities use chromic acid to form an oxide layer on aluminum to provide resistance to corrosion. The phase out was part of the National Emission Standards Hazardous Air Pollutants requirements with a compliance date of September 21, 2015. The rule is specific to PFOS and does not mention if the non-PFOS WA/FS can contain other PFAS besides PFOS.[206] Example products from the above described facilities are in Table 8.

PFAS dispersion products, which are used to coat metals, have been manufactured since 1951.[5] DuPont stated Zonyl FSN is used in plating to create foam to suppress acid mists and to reduce bath material drag.[17] Chemguard identifies similar uses for their fluorosurfactants.[16] PFAS also improve copper electroless plating quality and stabilize coating baths for depositing nickel-boron layers. PFAS are used in copper, nickel, and tin electroplating. They improve electroplating bath stability and enhance overall performance. Copper has been deposited from acid copper sulfate solution containing cationic and amphoteric PFAS. PFAS can be used as a leveling agent for zinc electrodeposition. PFAS can be used to treat metal surfaces to prevent corrosion, reduce mechanical wear, or enhance aesthetic appearance. They promote the flow of metal coatings and prevent cracks during drying.[11] Several PFAS are associated with metal plating.[12] Some are specifically mentioned as being used as a defoamer or foam dampening agents in the metal industry.[64,189] Machine parts have been cleaned after nickel plating with a solution containing PFOS.[11] Some PFAS are effective blocking agents for aluminum foil, which is said to be coated with 0.025 g/m^2 Monflor 91 applied as a 5% solution.[11]

U.S. EPA Region 5 sampled discharged process wastewater from 11 decorative chrome plating facilities, and all 11 discharged quantifiable PFAS concentrations above background levels.[207] A recent study by Michigan Department of Environment, Great Lakes, and Energy and U.S. EPA sampled nine current fume suppressants. In eight of the nine suppressants, they found only one PFAS in the targeted analysis of 25 PFAS. Nontargeted analysis found other PFAS.[208]

3.14 | Mining industry

PFAS may have been used as surfactants to enhance metal recovery from ores in copper and gold mines.[10,31,47] An aqueous solution comprising fluoroaliphatic surfactant may be used prior or during gold and silver extraction from the metal ore. It is said to improve the precious metals' leaching from the ore.[209] A fluoroaliphatic surfactant may improve aqueous acid leaching of copper from heaps of low grade copper oxide ore.[210] PFAS are used in the ore flotation process to separate metal salts from soil and in electrowinning of metals, including in nitrogen flotation to recover uranium. Aluminum and vanadium ore separation may use PFAS.[3,11,12] PFAS have been used in the mining industry as a mist suppressing agent.[64] The PFAS moieties described in an EPA proposed SNUR are described as being used in mining surfactants.[32]A concept was investigated for extracting uranium from seawater in a process that used PFAS as a surfactant in the extraction.[211]

3.15 | Oil and gas industry

PFAS may be used as surfactants to enhance recovery in oil or gas recovery wells.[10,11,31,47,160,212,213] They improve subterranean wetting, increase foam stability, and modify the reservoir formation's surface properties by lowering surface tension and foaming properties to well-stimulation additives.[12] PFAS polymers may be used in oil well elastomers.[214] Due to their stability at high temperatures and pressures, liquid fluorinated compounds may be used in well drilling, completion, or workover operations.[215] DuPont's Capstone fluorosurfactants and 3M's products were used as well stimulation additives.[31,216] Chemguard states their fluorosurfactants more efficiently foam solutions used to relieve hydrostatic blockage of gas wells. They reduce fluid loss, increase penetration, and improve proppant-carrying and particle-lifting capabilities. They also improve stimulation recovery.[18] The PFAS described in an EPA proposed SNUR are described as being used in oil well surfactants.[32] Numerous PFAS were detected in environmental media sampled from an oilfield in China.[213] PFAS have also been investigated for use as tracers in understanding geological communication in oil well development.[217,218]

A patent refers to the use of a fluorine-containing aromatic compound to allow lubricating oil to function well with refrigerants.[219] Petroleum-product storage tanks may use a floating layer of PFAS-treated cereal grains on top of the liquid surface to reduce evaporation loss. Similarly, evaporation of hydrocarbon fuel can be prevented by an aqueous layer containing PFAS.[11]

TABLE 9 Packaging, paper, and cardboard

Anticorrosion liner
Baking paper
Butter wrappers
Carbonless forms
Coated raw paper
Folding cartons
Food plates, bowls, etc.
General liner and flute
Kraft paper
Masking papers
Microwave popcorn bag susceptors
Neutral liner
Neutral white role paper
Paper combined with metal
Pet food bags
Pizza boxes
Paper food straws
Raw paper for plaster board
Take-out food containers and food wraps
Wallpaper
Wood-containing paper

Oil spills in water can be contained and prevented from spreading by injecting a chemical barrier containing PFAS into the water.[11] PFAS is said to improve concentration, collection, and control of an oil spill in water by helping to maintain an optimal oil slick thickness for skimming. One patent states that AFFF could be used for this purpose.[220] In addition, perlite or vermiculite treated with a cationic PFAS is claimed to be helpful in containing oil spills.[11]

3.16 | Packaging, paper, and cardboard

PFAS have been used to provide water and oil resistance to paper products for both food and nonfood use. Table 9 has a list of various paper products that have been associated with PFAS use. Different PFAS have been reported to be used with packaging and paper.[31,35,48,49,64,221] However, according to one report, three major types of PFAS have been used in the paper and packaging industry: side-chain fluorinated polymers in which the perfluoroalkane sulfonyl fluoride- or fluorotelomer-based alcohols, their acrylate or methacrylate esters are attached on side chains; phosphate ester salts made through the esterification of perfluoroalkane sulfonyl fluoride- or fluorotelomer-based alcohols with phosphoric acid; and perfluoropolyethers.[47] Extractable PFAS have been found in paper-based food contact material.[40,69,222-224] A patent notes that, previously, copolymer composition comprising a long-chain PFAS has been utilized as the water and oil resistant agent for paper. Due to concerns about long-chain PFAS, the patent discusses using a short chain fluoroalkyl group to apply the water and oil resistant agent to a pulp at a papermaking stage.[225] While almost all reports of PFAS use with paper products are with respect to oil and water resistance, they may have been used with wallpaper to avoid the paste permeating the wallpaper or to make it wipe clean.[35]

PFAS food contact uses primarily cover their waterproofing and grease-proofing properties in paper and paperboard products. They are used as surfactants in emulsion reactions, as reactants for the manufacture of low-molecular-weight perfluorinated polymers and as monomers in high molecular weight polymers. Packaging includes food contact paper and paperboard products particularly those in contact with oily foods and nonfood contact applications.[10,11]

Perfluorooctyl sulfonamido ethanol-based phosphates were the first substances used to provide grease repellence to food contact papers, followed by fluorotelomer thiol-based phosphates and polymers' use. The fluorosurfactants were added to the paper through the wet end press where cellulosic fibers are mixed with additives. The phosphate-based fluorinated surfactants provide good oil repellency but have limited water repellency. Hence, acrylate polymers with fluorinated side chains derived from sulfonamido alcohols and fluorotelomer alcohols were very widely used polymers when oil, grease, and water repellence was needed.[12] A common PFAS usage was with molded pulp food contact materials.[221] When added to the pulp, fluoroalkyl phosphate needs to be added at 1.0%–1.5% based on dry fiber weight to provide good oil repellency.[11] However, a Swedish Chemicals Agency report notes that a product registry contains perfluorinated substances registered under the functions of impregnating or surface treatment for paper. The report states these may be used by converters, which purchase paper products and then may treat them with fluorinated chemicals, rather than paper mills.[35] Recently, there have been reports indicating potential use of perfluoropolyether-based phosphates and polymers for treatments of food contact paper and paper packaging.[12,226]

In the United States, the Food and Drug Administration (FDA) regulates PFCAs as indirect food additives for food contact due to their use as surfactants and their role in the polymerization of high-molecular-weight food contact substances. FTOHs are monomeric constituents of these food contact substances, used as coatings for their grease-proofing properties under several effective food contact notifications. In 2016, FDA announced that it would no longer provide for the use of certain PFAS in food contact paper and paperboard.[227] Separately, FDA also announced that it would no longer provide for the use of certain perfluoroalkyl phosphates and acrylate copolymers in food contact paper and paperboard.[228]

3.17 | Pesticides and fertilizers

PFAS have been used as an active and inert (or inactive) pesticide ingredient. Their status as either active or inactive ingredients currently seems to be governed by country-specific rules. Active ingredients are those that kill the intended pest, while inactive ingredients help the active ingredient by helping it get to or stay on the surface being protected.[229]

The list of compounds in "PESTICIDES | EPA: List of Active Ingredients UPDATED 10/25/2019" in EPA's Chemicals Dashboard was compared to the compounds in "PFAS | EPA: PFAS structures in DSSTox," also in EPA's Chemicals Dashboard.[14] Eight compounds were common to both lists and are listed in Table S1. The identifiers were then checked in EPA's Pesticide Chemical Search,[230] EPA's Pesticide Product and Label System (PPLS),[231] and Purdue University's National Pesticide Information Retrieval System (NPIRS),[232] and the names were searched for in the Federal Register.

PFAS may be used as inert surfactants in pesticide products.[47] However, in the United States, PFAS no longer appear to be used as pesticides additives. A search of the "PESTICIDES | EPA: List of Inert Ingredients Food and Nonfood Use UPDATED 10/25/2019" in EPA's Chemicals Dashboard was compared to the compounds in "PFAS | EPA: PFAS structures in DSSTox," also in EPA's Chemicals Dashboard. No compounds were found in common. Having no historical list, the website does not support a search to determine what was previously allowed.[14]

Other sources note PFAS used in pesticide formulations.[10,12] PFAS can be used as herbicidal dispersants and wetting agents and to aid wetting and penetration in insecticides.[11] A patent for an insecticide is based on novel bis-amide derivatives where numerous substitutions on the molecule can be PFAS-based groups.[233] Another patent is for insecticidal and fungicidal composition where much larger molecules in the composition have branches composed of perfluoroalkyl chain molecules.[234] Similarly, other pest control patents refer to a compound derivative where some of the side chains are composed of perfluoroalkyl.[235-237]

Perfluoroalkyl phosphonic acids and perfluoroalkyl phosphinic acids have been used as inactive pesticide ingredients.[12] Patents repeatedly indicate their use as foam-breaking agents for herbicidal, fungicidal, or insecticidal mixtures so that, when sprayed, the leaf is properly wetted.[238] One patent also mentions PFAS and states the antifoaming agents typically amount to at least 0.01% and not more than 3% of the composition by weight.[239] Yet another patent mentions the same PFAS groups for similar uses in concentrations of 0.1 to 20 g/L.[240] Other patents discuss the same or similar PFAS and their uses.[241-244] Fluorotelomer alcohol-based phosphates were also approved as inactive ingredients.[12] In 2006, the United States (U.S. EPA) revoked their use for this purpose; the revocation became effective in 2008.[245]

PFAS may have been used in fertilizers also. A patent refers to coating fertilizer particles with PFAS polymers to reduce dust. Numerous PFAS monomers are referred to as being coating ingredients.[246]

3.18 | Photography and lithography industries

PFAS have been used in manufacturing film, paper, and plates as both dirt rejecters and friction control agents as well as to reduce surface tension and static electricity.[10,11,247] AGC notes that their SURFLON fluoro-surfactants decrease surface tension, providing improvement in wetting, penetration, and leveling properties for applications, such as photographic emulsions.[34] An EPA SNUR in 2002 and 2007 lists their use "in coatings for surface tension, static discharge, and adhesion control for analog and digital imaging films, papers, and printing plates, or as a surfactant in mixtures used to process imaging films and states these are not considered new uses."[131,248] Another SNUR refers to use in photo media coatings.[15]

Several PFAS have been used in this industry.[10,12,49,107] Commenting on a PFSA SNUR, Kodak noted that telomers had been reviewed as PFSA replacements.[247] Photography industry PFAS users include producers of consumer film, X-ray film for medical and industrial use, and the movie industry.[10] PFAS can be added to photothermographic material used for medical diagnostics to stabilize the material in storage.[249] Optical film may use PFAS to prepare the dissolved cellulose ester for casting. Optical film may also have a fluorine-containing resin for a low refractive index layer.[250] The photography and photolithography industry also has used PFAS as antireflective agents.[64,134] They were used in photosensitive lithographic plates to facilitate control of the development process.[11] PFAS are also used in the photolithography process for semiconductors as discussed below.

3.19 | Plastics, resins, and rubber

Numerous PFAS have been used as processing aids, raw material, or manufacturing intermediate in fluoropolymer production. Fluoropolymers, which can be made into plastics, have hundreds of uses in consumer and industrial products, as noted elsewhere in this paper, such as the textile, medical industry, in critical industrial applications.[3,25,107] The first fluoropolymer patent application was filed in Germany in 1934 by Schloffer and Scherer. PTFE was originally synthesized in 1938.[7] Different plastic products where PFAS is used are listed in Table 10.

PFAS are used as mold-release agents for thermoplastics, polypropylene, epoxy resins, and polyurethane elastomer foam molding. PFAS have been used in formulations for anti-blocking agents for vulcanized and unvulcanized rubbers. PFAS in silicone rubber sealants make the seal soil resistant. PFAS improve wetting of composite resin fibers or fillers and speed the escape of bubbles.[11] Fluoropolymers can be spun into fibers to make consumer and industrial products.[26,95,251,252] ETFE is a film that can be used as a structural glass alternative; multiple layers are attached to a metal frame.[26]

Fluoropolymers can be made directly by combing fluorine and a nonfluorinated polymer. Fluorination occurs as a separate step or during the manufacturing of polyethylene bottles via blow molding using dilute fluorine. Fluorination surface treatment improves the resistance of polyethylene to many organic chemicals. The fluorination of the surface reduces the solubility of organic liquids in the plastic, thus reducing permeation through the wall of the bottle.

TABLE 10 Plastics, resins, and rubber

Aerospace equipment
Agricultural chemical containers
Architectural coatings
Architectural fabrics
Automobile components
Automotive fuel hoses
Caustic potash electrolyzer membranes
Caustic soda electrolyzer membranes
Chemical containers
Chemical handling parts
Chemical plant equipment
Chlor-alkali cell membranes
Citrus product containers
Cleaning chemical containers, household, medical, and industrial
Cookware
Cords
Corrosive liners
Electrical cable insulation and jacketing
Electronic chemical containers
Emission control apparatus membranes
Expansion joints/bellows
Fishing line
Flavor, fragrance, and essential oil containers
Food processing equipment
Fuel cell membranes
Gaskets
Geotextiles
High purity piping
Hydrocarbon containers and tanks
Instrument strings
Linings (ex. vessels, valve, pipes)
Medical processing equipment
Oil and gas drilling equipment
Paper and pulp industry components
Pesticide containers
Pharmaceutical processing components
Photography chemical containers
Polish containers
Racquet strings

(Continues)

TABLE 10 (Continued)

Rope
Seals
Semiconductor piping
Sewing thread
Stone and tile care product containers
Sutures
Tubing
Water electrolyzer membranes
Wax containers

Fluorine-treated bottles are excellent for use with numerous chemicals. For nonbottle applications, fluorination of plastic can provide compliance with state and federal regulations, such as with fuel tanks.[25] However, this process, which does not use nonpolymer PFAS, may create nonpolymer PFAS. Rinsate samples of directly fluorinated high-density polyethylene, which had not been used for their intended purpose of containing pesticide, were found to have nonpolymer PFAS.[253]

A patent for a shell-side contactor used to form ozonated water uses perfluoroalkoxy resin hollow fibers.[254] PFAS are used to make perfluorinated membranes, first invented in 1962, used in industrial processes.[255] From the mid-1960s, Nafion was used as an electrochemical separator material in the chlor-alkali industry.[25,118] A patent refers to perfluorinated membrane use in emission control apparatus for combustion flue gas streams.[256]

Perfluoroelastomers are materials known for their high chemical resistance, plasma resistance, acceptable compression set resistance and good mechanical properties. They work well in high temperatures and harsh environments, such as those associated with corrosive fluids, solvents, lubricants, and when oxidizing or reducing conditions are implicated.[257,258] One of PTFE's first reported uses was in 1943 with the Manhattan project, which required corrosion-resistant liners and gaskets for reactors and valves to handle highly corrosive UF_6.[137]

Numerous reported PFAS are used in fluoropolymer manufacturing as a processing aid, intermediate, or additive.[1,5,64,107,134,259-261] PFBS has been used as a flame retardant for polycarbonate and as a plastic additive.[47,64,262] Flame-retardant polycarbonate compounds, where polycarbonate is the base resin, are described as PTFE lubricated.[263] Extractable PFCAs have been found in thread seal tapes and pastes and nonstick cookware.[40]

3.20 | Recycling and material recovery

Metals, in particular rare earth metals, can be recovered from metal waste using solvent extraction processes that use PFAS. In tests, some heavy metals were recovered at 100% efficiency after two extractions steps, and the solvent could be reused.[264] Similarly, others have recovered high percentages of palladium from multi-layer ceramic capacitors in electrical and electronic equipment waste using liquid extraction with PFAS surfactants.[265] Indium can be recovered from liquid crystal displays using PFAS in homogeneous liquid–liquid extraction (HoLLe) during recycling.[266] The HoLLe process with PFAS has also been investigated for recovery of platinum group metals from plating wastewater.[267,268]

Supercritical carbon dioxide with PFAS surfactants have been investigated to remove radioactive cesium from contaminated soil. In the research, high extraction percentages were achieved from soil and sand.[269,270] It has also been investigated for removing cesium from contaminated concrete with less success.[271] Other have used it for a variety of radioactive and nonradioactive heavy metals from solid and liquid media.[272–274]

Fluorosurfactants have also been investigated for use in regeneration and recovery by thermal distillation of n-hexane from waste gases. The PFAS are in an aqueous solution and can be reused.[275]

3.21 | Refrigerants

PFCs are perhaps most commonly known as refrigerants. Many have physiochemical properties that make them ideal for use in air conditioning, refrigeration, etc. The list of compounds in "LIST: Refrigerants—small molecule halocarbons" in EPA's Chemicals Dashboard was compared to the compounds in "PFAS | EPA: PFAS structures in DSSTox," also in EPA's Chemicals Dashboard.[14] There were 79 chemicals, listed in Table S1, that are common to both lists. The majority of these chemicals are PFCs or fully halogenated alkanes of carbon length 2–9. These chemicals are also listed in Table S1.

3.22 | Scientific, general use

Various PFAS have been used in general laboratory work. Trifluoroacetic acid has become the ion-pairing agent of choice for reversed-phase high-performance liquid chromatography of peptides and proteins, but other PFAS have also been investigated for this use.[276] Several PFAS can be used as derivatizing agents for gas chromatography or laboratory analytical reagents.[64,277] PTFE is used frequently in scientific equipment, including chromatography needles, syringe filters, bottles, caps, closure linings, etc.[278,279]

PFAS have been mentioned as tracers for various types of scientific investigations. This type of tracer use is different from the radiotracers mentioned in the medical use section but is similar to the tracer use mentioned in the oil and gas industry section. Volatile perfluorocarbon tracers can be used to measure air dilution and exchange such as between a home's indoor and outside air.[280,281] They have been used as tracers for long range atmospheric and air pollution studies.[282,283] PFAS can also be used as geological tracers underground. They have been noted for use in studying stream discharge and groundwater flow direction.[284] They were also used to test a subsurface barrier integrity,[285] to detect nonaqueous phase liquids,[286] and to investigate geothermal systems.[287] PFAS were also investigated for use as marine tracers.[288] In studying carbon dioxide geological sequestration, hydrophilic and hydrophobic PFAS are mentioned as tracers co-injected with the carbon dioxide.[289,290] Similarly, they have also been investigated for detecting leaks from high-pressure, fluid-filled cables such as electric feeder lines. PFAS can be injected into the fluid in the cables and then monitored above ground to locate a leak.[291,292]

3.23 | Semiconductor industry

PFAS are used in the semiconductor industry to reduce surface tension and reflectivity of etching solutions to facilitate precise photolithography.[10,11,107,134] EPA 2002 and 2007 SNURs list their use "as a component of a photoresist substance, including a photo acid generator or surfactant, or as a component of an antireflective coating, used in a photomicrolithography process to produce semiconductors or similar components of electronic or other miniaturized devices."[131,248] A public comment letter associated with this SNUR's proposal noted that this same process is used to produce semiconductor and electronic components for disk drives, electronics packaging, micromachines, and optoelectronic devices and circuits.[293] They are used in liquid etchant in the photo mask rendering process.[10] Fluoropolymers are used in the semiconductor industry for process surfaces, wafer carriers, tubing, valves, pumps and fittings, and storage tanks.[7,25] PFAS can be used as a working fluid in vacuum pumps in the semiconductor manufacturing process.[3]

A patent suggests using PFAS as surfactants for use in extreme environments, including etching solutions in semiconductor device preparation, electrochemical plating and polishing solutions, wafer cleaning and polishing solutions, anisotropic etching solutions, electrolytes for alkaline batteries, and developer solutions for semiconductor manufacturing.[294] Another patent describes etching solutions for integrated circuits as being improved with the addition of fluoroalkylsufonate surfactants. The surfactant is described as having a concentration between 25 and 20,000 ppm in the etching solution.[295] Other lithography patents related to semiconductors refer to PFAS and PFAS-derived polymers use.[296,297] A patent describes PFAS use for cleaning or polishing silicon or gallium arsenide, silicon or gallium arsenide wafers coated with thin films of various compositions including metals, conductive polymers, insulating materials, and copper-containing substrates, such as copper interconnects. The cleaning includes a surfactant from 10 to 1000 ppm of perfluorinated sulfonamide.[298]

3.24 | Textiles

The textile industry uses PFAS extensively for their ability to repel oil, water, and stains. PFAS dispersion products, which are used to coat

TABLE 11 Textiles

Automobile interior parts
Awning textiles
Carpets
Clothing apparel
Fire fighters protective clothing and gear
Gloves
Home textiles
Industrial environment textiles
Jackets
Leather
Medical garments
Outdoor textiles
Sails
Shoes
Tents
Umbrellas
Upholstery

fabrics, have been manufactured since 1951.[5,49,299,300] Many types of outerwear, household products, interior automobile parts, and outdoor equipment are also treated with PFAS and listed in Table 11.[10,31,35] For textiles, treatment can be done pre-market, or textiles can be treated after market with consumer applications.[31] Typically, 0.05%–0.5% of the fluorochemical by weight of the textile is used to deliver durable repellency. The repellents are applied to the textiles and carpets in mills as aqueous dispersions, and in some after-market applications, as solutions in halogenated solvents.[3] Premarket treatment generally uses perfluoroalkyl groups attached to acrylic or urethane polymer backbone, which attaches to the textile.[7,47] Protective clothing for fire fighters can be surface treated with PFAS or made from woven fluoropolymers.[47] Similarly, medical garments may be treated with side-chain fluorinated polymers as previously discussed in the medical industry section.[47]

Numerous PFAS are associated with the textile industry, especially with treatment of the textiles, and more recently shorter chain PFAS have replaced the longer chains.[15,31,48,189,301,302] Various companies have made fluorinated chemicals for use on textiles, including DuPont (Zonyl, Captone, and Foraperle), 3M (Scotchgard), Clariant (Nuva), Bayer (Baygard), Ciba (Oleophobol), Daikin (Unidyne), and Solvay Solexis (Fluorolink).[90,303] Extractable PFCAs were found in pretreated carpets, treated apparel, gloves, home and outdoor textiles, leather, and awning textiles.[40,69] A 2013 SNUR made it a significant new use to use the associated long-chain perfluoroalkyl carboxylate for use as part of carpets or for treating carpets.[33] Fluoropolymers can also be spun into fibers and used to make luggage, sailcloth, and fabric for fire suppression needs.[25] High

TABLE 12 Transportation

Automotive break lines and fuel lines coating
Automotive textiles
Automobile trim
Aviation hydraulic fluid additive
Fuel cell separators
Fuel tanks and fuel tank bladders
Gaskets, flat or lathe-cut
Hoses
Interior paneling of passenger aircraft
O-rings
Shaft seals, lip-type rotating or reciprocating
V-rings
Valve stem and seals
Wiring jacketing and insulation

molecular mass PTFE can be fibrillated to make highly porous fabrics, which are widely used in outdoor wear and camping accessories.[47] Textiles made from fiberglass coated with or saturated with PFAS can also be used for high temperature or corrosive industrial environments. Kevlar and perfluoroplastic composite textiles can also be used for similar industrial environments.[304] Textiles made from polymers are discussed further in the plastics section.

3.25 | Transportation industry

PFAS have been used in various parts of the transportation industry such as car manufacturers, airplane manufacturers, shipping industry, etc. as shown in Table 12, but many of the uses are mentioned in other sections. For example, electronics are used in all aspects of transportation, so many of the uses of PFAS for electronics, such as wire coating, would be applicable to electronics in transportation. ETFE resins are used for jacketing and insulation of electrical cables, including control wiring in aircraft and other transport systems.[3] They can be used to coat automotive tubing.[25] Fluoropolymers have been used for various components in this industry. PVF-clad metal or plastic laminates are used to coat wall and ceiling panels in passenger aircraft and automobile trim.[3,25] In automotive equipment, fluoropolymers' mechanical properties are beneficial in low-friction bearings and seals that resist attack by hydrocarbons and other fluids.[25] Fluoroelastomers are used extensively by aircraft, aerospace, and automotive industries, as they maintain their rubber-like elasticity at high temperatures and in contact with various chemicals. They are primarily used in sealing applications under compression and rarely under tension.[3]

PFAS may be used as evaporation inhibitors for gasoline, and as jet fuel and hydrocarbon solvents.[10] PFAS have been used in civil and military hydraulic oils to prevent evaporation, fires, and corrosion.[10] Their use as an anti-erosion additive in fire-resistant phosphate ester aviation hydraulic fluids is listed in a US EPA SNUR in 2002 and 2007 as not being a new use and not applicable to the rule.[131,248,305–307]

4 | CONCLUSION

PFAS' particular properties have led to their use in a wide variety of applications. They have been used since at least the 1950s in both consumer, commercial, and industrial applications. The uses discussed here may not be exhaustive, as other uses may exist, including uses outside the United States. PFAS are used in many applications where the use is considered proprietary and not readily available or public. Patent searches provide valuable information about different uses, but many patents provide only general information on chemicals used. The chemicals needed for many patents tend to be performance-driven, so the available information often only conveys the chemical attributes necessary to achieve the requisite properties instead of identifying the exact chemical.

PFAS nomenclature in general, as well as individual PFAS names, have been inconsistent through the years. The terms PFAS, PFC, fluorosurfactant, fluorochemical, and others have been used and are still being used. Also, there is no official definition of what is and is not a PFAS. EPA's Chemicals Dashboard PFAS structures list was used to compare to other lists as described above.[14] However, the definitional conflicts point to problems identifying which PFAS have been used in some cases. If there is no agreement as to whether a particular compound is a PFAS, then that lack of clarity leads to disagreements as to whether a PFAS was utilized in either a particular industry or for a particular use. Also, it should be noted that a particular use may reference a PFAS, such as potassium salt, but if the compound is released into the environment or a worker is exposed to it, the respective acid, or ion, will have the potential to be found in the environment or the worker's serum.

As presented here, PFAS have been used in numerous applications and industries. In many applications, however, it is difficult to determine which PFAS were used and in what amounts. This difficulty impedes understanding the potential for exposure or contamination related to that application both in the workplace and in the environment. Numerous factors can affect if the use of PFAS in an application has the potential to lead to occupational exposure or release to the environment. There is more potential for occupational exposure if the application can lead to aerosolization or volatilization of PFAS. Occupational exposure or release to the environment can also depend on whether the application is in an open or closed system. Workers may be protected from PFAS exposure with engineering controls and/or personal protective equipment, which may be used to protect against other hazards. Release to the environment may be reduced or prevented by facility air controls, wastewater treatment, and waste management. Further, the potential for PFAS to cause contamination is also dependent on whether PFAS will leach or breakdown from the industrial or consumer product where it is used or disposed.

Waste management is another potential source of worker exposure and environmental release. With the exception of the recycling and material recovery uses mentioned above, waste management is not an industry where PFAS is used. Conversely, waste that contains PFAS is managed by the waste management industry. Consumer waste and industrial waste are sent to landfills, incinerators, recycling facilities, etc. Workers in these industries have potential exposure to PFAS, and these industries likewise have the potential to be a source of PFAS released to the environment.

As described above, in some applications, PFAS was only a small percentage of a mixture, which could decrease the potential for contamination should a release occur. PFAS contamination is associated with AFFF use, and AFFF ranges from 1% to 6% concentrate to water. However, the application of AFFF to a fire is a different scenario, though, than most other PFAS applications. AFFF has been used in firefighting training and actual firefighting, where it was applied directly onto the ground. The used AFFF often was then allowed to go down stormwater drains or migrate into the soil. Conversely, fire fighters would generally wear personal protective equipment while using the AFFF, thus minimizing their exposure. However, they may be exposed while cleaning the equipment after using AFFF.

Conversely, PFAS has been used in metal plating, in particular hard chrome plating, to control chromium emissions. PFAS suppress mists at the surface of an electroplating bath to inhibit chromium emissions.[203] Ironically, this PFAS use protected the workers and environment from chromium emissions, but it could lead to PFAS exposure. A study of decorative metal plating facilities found they released PFAS in their process wastewater.[207] Metal plating occupational exposure to the PFAS has not been studied based on literature searches.

For many PFAS applications, more information is needed to understand their exact use and the amount of use. The specific use in a given application is critical to determining whether there is the potential for human or environmental PFAS exposure. When investigating potential occupational or environmental exposure, it is important to understand all the possible sources of that exposure.

AUTHOR CONTRIBUTION

Linda Gaines conceived the manuscript, performed the literature review, wrote the manuscript and is responsible for all work.

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CONFLICT OF INTEREST

The author declares no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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